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Lightning detection rates and wildland fire in the mountains of northern Baja California, Mexico

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RESUMEN

Los ecosistemas de chaparrales y bosques de coníferas del norte de Baja California se queman repetidamente debido al clima mediterráneo que presenta la región. La alta frecuencia de incendios se ha atribuido a la quema deliberada. Sin embargo, los rayos que ocurren durante las tormentas de verano son causa de igniciones naturales frecuentes. El Sistema de Detección de Rayos de los Estados Unidos localiza y registra las descargas eléctricas en esta región. Estos datos se introdujeron al sistema de información goegráfica ARC-INFO en el cual se calcularon las tasas de detección de rayos en los diferentes tipos de vegetación. La densidad de los rayos detectados es mayor en las zonas de movimiento ascendente del aire a lo largo de la vertiente oriental de las Sierras de Juárez y San Pedro Mártir. De 1985 a 1990 hubo de 17 a 46 veces más rayos que incendios en ambas sierras. Los periodos refractarios de la vegetación -el tiempo transcurrido entre dos incendios consecutivos- son largos (70 a 82 años). Una superficie de 1000 hectáreas, que es el tamaño promedio de un incendio en Baja California, recibe un número importante de rayos en pocos años. En consecuencia, son pocos los rayos que ocasionan incendios debido a la escasez de biomasa combustible. Los largos periodos refractarios de la vegetación ponen en evidencia una relación inversa entre el número y el tamaño de los incendios. Dada la alta tasa de detección de rayos, las igniciones provocadas por el hombre tendrían, por lo tanto, poco impacto sobre los regímenes de incendios.

ABSTRACT

Chaparral and conifer forest ecosystems in northern Baja California are subject to recurrent fire owing to the regions's mediterranean climate. The high frequency of burns has been attributed to deliberate burning. However, lightning from summer thunderstorms are a frequent source of natural ignitions. The US lightning detection (LD) data system records and locates lightning discharges in this region. These data were entered into the ARC-INFO geographic information system (GIS) in which were calculated LD rates within vegetation types. LD densities are greatest in updraft zones along the eastern escarpments of the Sierras Juárez and San Pedro Mártir. From 1985 to 1990, there were 17 to 46 times as many lightning discharges as burns occurring in both sierras. The fire refractory periods -the time between consecutive burns- are long (70-82 yr). An area of 1000 ha, which is the average size of burns in northern Baja California, receives a number of lightning strikes every few years. Consequently, few lightning strikes give rise to fire due to the scarcity of combustible biomass. The long refractory periods of the vegetation provide evidence of an inverse relation between the number and the size of burns. Given the high rates of lightning detection, ignitions provoked by man would have little impact on fire regimes.

Introduction

The Pensinsular Ranges of northern Baja California are covered by Californian chaparral and conifer forests found nowhere else in Mexico (Rzedowski, 1978; Minnich, 1987a). These ecosystems are subject to recurrent fire owing to the region's Mediterranean climate. Abundant plant cover, supported by winter rains, is desiccated during the summer drought. High inflammability is encouraged by accumulations of dead foliage, litter, and cured herbaceous cover. Analysis of 20th century fire perimeters, reconstructed from Landsat imagery, and historic and recent aerial photographs, reveal a pattern of numerous burns throughout the mountains of northern Baja California (Minnich, 1983, 1989). Fire rotation periods –the time required for a zone covered with vegetation to be completely burned– average 50–70 years in chaparral and conifer forests growing on the mesic near–coast ranges and western slopes, then increase to 200+ years in pinyon forests along the arid eastern escarpments.

The high frequency of burns in Baja California has been attributed to deliberate burning (Keeley *et al.,* 1989). Aerial photographs of the Sierra Juárez show that burns often establish along roads, trails, meadows, and canyons; this suggests of anthropogenic firing of the vegetation, a common practice among cattlemen and farmers in northern Baja California (Freedman, 1984). However, lightning from thunderstorms is a frequent source of natural ignitions during the summer months. Trees damaged by lightning can be seen throughout the mountain forests. State and federal forest fire control crews extinguish fires initiated by lightning every summer.

To date, direct evidence does not exist as to the role of man and lightning in the establishment of fires. Fire history data was not compiled by Secretaría de Agricultura y Recursos Hidráulicos (SARH) and other land management agencies until 1984, and lightning–initiated burns are not recorded. Moreover, the occurrence of fires in wildland ecosystems is not merely a response to ignitions, but requires the combination of ignitions striking vegetation capable of supporting burns (Minnich, 1988). Human–induced fires, by removing fuels, influence future lightning fires, and conversely (Minnich, 1987b). In the present work, we make no attempt to determine the relative importance of man versus lightning in inducing fires. Our interest here is to determine if the quantity of burning which has been experienced in Baja California during the present century can be brought about exclusively by lightning.

In 1985, the Bureau of Land Management installed the Lightning Detection System in the western United States (German, 1990a, b). This system consists of a network of 33 electromagnetic direction finders that record radiation emitted by all cloud–to–ground lightning strikes. Each sensor has a range of 400 km radius. Lightning strikes are located by triangulating signals from at least two sensors to a map resolution of approximately 8 km. Cloud–to–cloud discharges are not detected. Although the system is designed for fire suppression management in the western United States, lightning detection data exists from the mountains of northern Baja California because the computerized database grid extends south to latitude 31°N in order to accommodate the southernmost borders of the States of Arizona and New Mexico.

In this paper, we describe the climatology of the summer thunderstorm season in the Peninsular Ranges of northern Baja California, and analyze the frequency and distribution of lightning detections. We then discuss the significance of lightning in relation to the history of fire in chaparral and conifer forests over the past 70 years. Finally, we discuss how the results should be applied to the management of these ecosystems in Mexico.

Methods

Lightning detection (LD) data were obtained for two areas of northern Baja California (NBCA): 1) the northern half of the Sierra Juárez (SJ) where the chaparral fire history previously was

compared with that of adjacent southern California (Minnich, 1989) and 2) the Sierra San Pedro Mártir (SPM) within the database (north of lat 31°) (Fig. 1). The files include the location of lightning strikes by latitude and longitude, and the date of the detection. The data were entered into the ARC-INFO Geographic Information System (GIS) (Environmental Systems Research

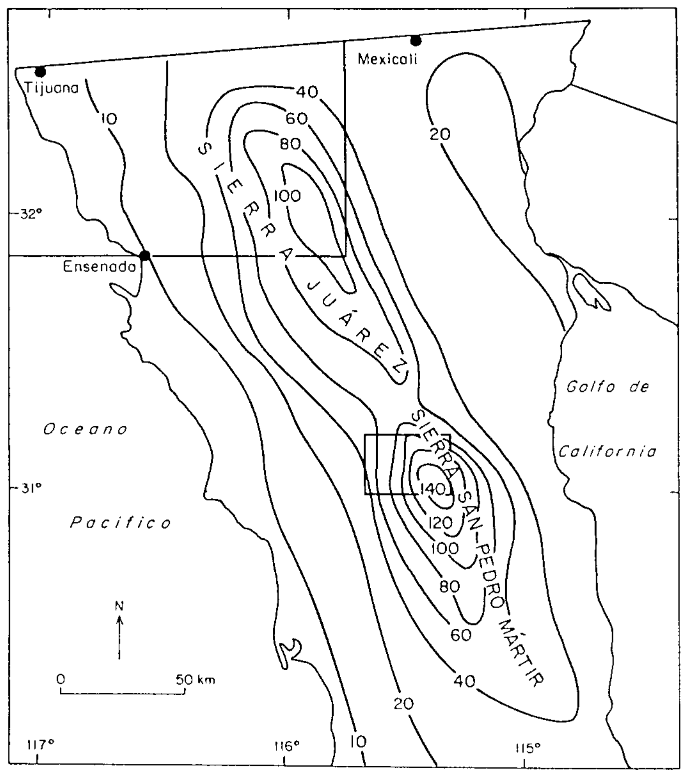


Fig. 1. Mean July to September precipitation (mm) in northern Baja California interpolated from averaged and normalized data. (Source: Secretaría de Agricultura y Recursos Hidráulicos, División Hidrométrica y Grupo de Meteorología, CICESE, Ensenada, Baja California). Insert grids are selected regions for lightning detection data analysis. The Sierra Juárez inset includes the area from lat. 31° 50' N to the international border and west of longitude 115° 30'. The Sierra San Pedro Mártir inset includes the area between latitude 31° 00' to 31° 15' N and 115° 20' to 115° 40' W.

Institute, Redlands, California), using a VAX 8820 computer. The ARC-INFO GIS is a vector-based GIS with a management system designed specifically for data entry and spatial analysis. In the GIS, we calculated LD rates within vegetation types; this was then related to data on summer precipitation estimated by normalization procedures. The results were also compared with fire history reconstructed from aerial photos for the period 1920–72 in the SJ (Minnich, 1989) and for 1920–1990 in SPM.

The Mexican monsoon

During the summer (July–September), the western margin of the North American monsoon, a deep layer of moist unstable tropical air, periodically extends to the sierras of Baja California Norte. This monsoon circulation permits the development of convective clouds with strong electrical charge. Satellite imagery shows the development of a wide belt of cumulonimbus

during the afternoon over the Mexican altiplano and Sierra Madre Occidental, northward into Arizona and New Mexico and westward to the Sierra Juárez and Sierra San Pedro Mártir. When unstable air extends west to the Pacific coast, a secondary narrow line of cumulonimbus develops over the mountains of Baja California.

In NBCA, the occurrence of thunderstorms is related to the position of the upper-level anticyclone found over subtropical latitudes of North America during the summer (Figs. 2 and 3; Hastings and Turner, 1965; Pyke, 1972; Reyes and Cadet, 1988; Reyes *et al.*, 1988; Meitín *et al.*, 1991). When the polar-front jet stream is displaced southward into Oregon or California along the Pacific coast, the upper level anticyclone is normally positioned over northern Mexico. As a consequence, the region is dominated by dry, southwesterly winds aloft (Fig. 2A). Over the Gulf of California, in the lower levels, tropical air moves northward over Sinaloa, Sonora and Arizona. The Pacific slope of the Peninsular Range is influenced by a layer of coastal clouds (fog) formed by the cooling of humid lower tropospheric air over the cold California Current.

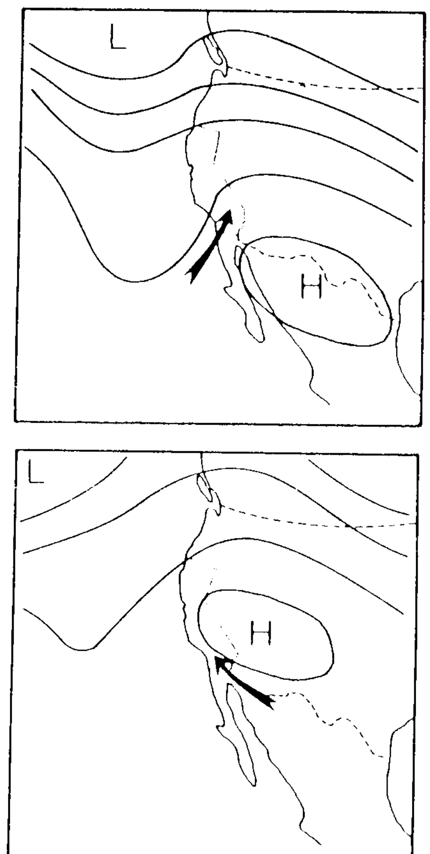
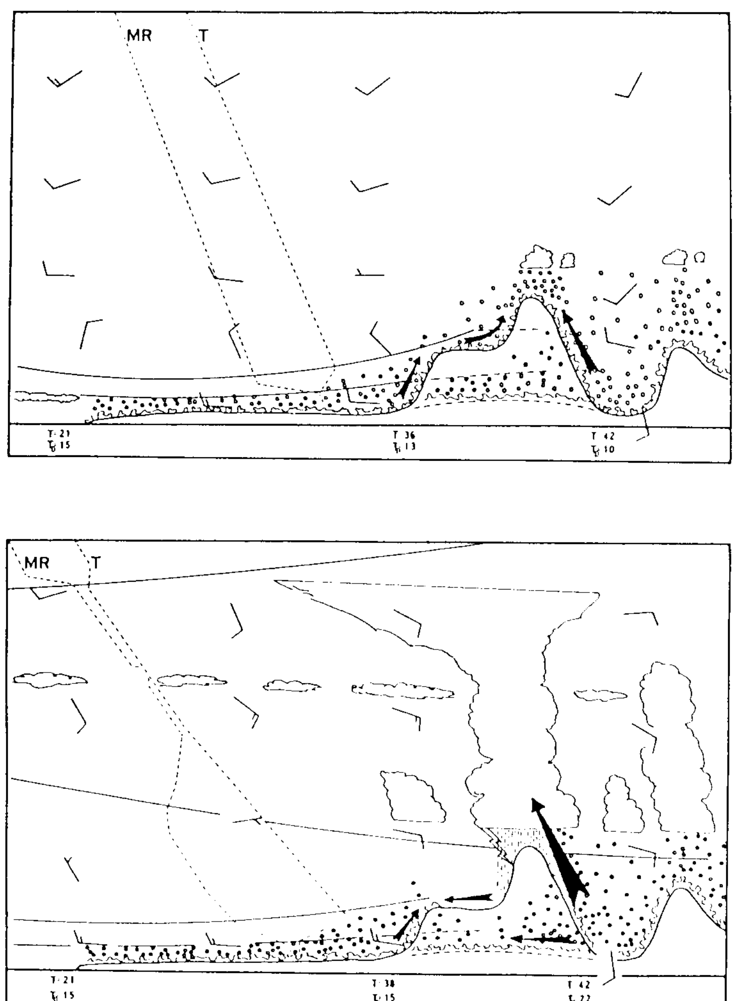


Fig. 2. July to September 500 mb circulation models for: (A) dry southwesterly flow and (B) southeasterly Mexican monsoon thunderstorm types in northern Baja California.

This layer is covered by a strong thermal inversion. Marine breezes from the northwest, valley wind circulations, and mountain slope winds, transport stable marine air inland toward the higher sierra, in a manner similar to that which occurs in the mountains of southern California (Edinger 1959, 1963; Edinger *et al.*, 1972; Schroeder *et al.*, 1967; Glendening, 1986). Data on mean temperatures for several stations in Baja California show a temperature inversion between 500–1000 m on the west slopes of the mountains (Alvarez and Maisterrena, 1977). In spite of the dissipation of the inversion on the warm mountain slopes during daylight hours the movement of

the wind from the valleys towards the mountains produces a rapid mixing with the overlying dry air in this zone that impedes any significant convection. To the east of the Sierra, the descent of air produces low dew points over the deserts (Fig. 3A).

As the monsoon circulation intensifies during the summer months, south and southeast winds aloft transport tropical moisture towards (NBCA) (Fig. 2B). The fluxes of tropical moisture of the lower troposphere (<800 mb), apparently initiated by tropical cyclones off the west coast of Mexico, move northeast along the Gulf of California and toward the adjacent desert plains and Arizona (Hales, 1972, 1974). Surface winds along the Gulf and adjacent deserts turn south to southeasterly and dew points increase to 15–25°C. Satellite imagery shows that air masses tend to be unstable only over high terrain. Moist low-level air masses from the Gulf of California convect orographically up the eastern escarpments of SJ and SPM during afternoon hours (Fig. 3B). A secondary line of cumulonimbus tends to form along the chain of coastal ranges southeast of Bahía Todos Santos.



A

B

Fig. 3. Conceptual model of afternoon weather conditions for: (A) dry southwesterly flow and (B) southeasterly Mexican monsoon thunderstorm types. T = hypothetical atmospheric temperature profiles. MR = hypothetical mixing ratio profiles. Chaotic lines and bubbles represent superheated air and updrafts. Barbs show wind directions and velocities aloft.

Cumulonimbus cells that form over updraft zones of the sierra dissipate when upper-level south to southeasterly steering winds move storms toward the Pacific coast away from convection sites. Standing cumulonimbus are occasionally observed along the crest of the sierra; as old cells dissipate, they are replaced by newly-developing ones. These clouds cause rains that may last several hours. On the western slopes convection does not occur due to the presence of slope winds ascending from the Pacific. Skies along the coast are typically clear except for scattered altocumulus and cirroform layers. Low stratus occurs along the beach and a few km inland.

Precipitation during the summer thunderstorm season (July–September) averages from 100–150 mm along the crest of SPM and SJ (Fig. 1). Moderate summer precipitation also extends into the desert east of SPM. Thunderstorms forming over this range frequently drift over this area

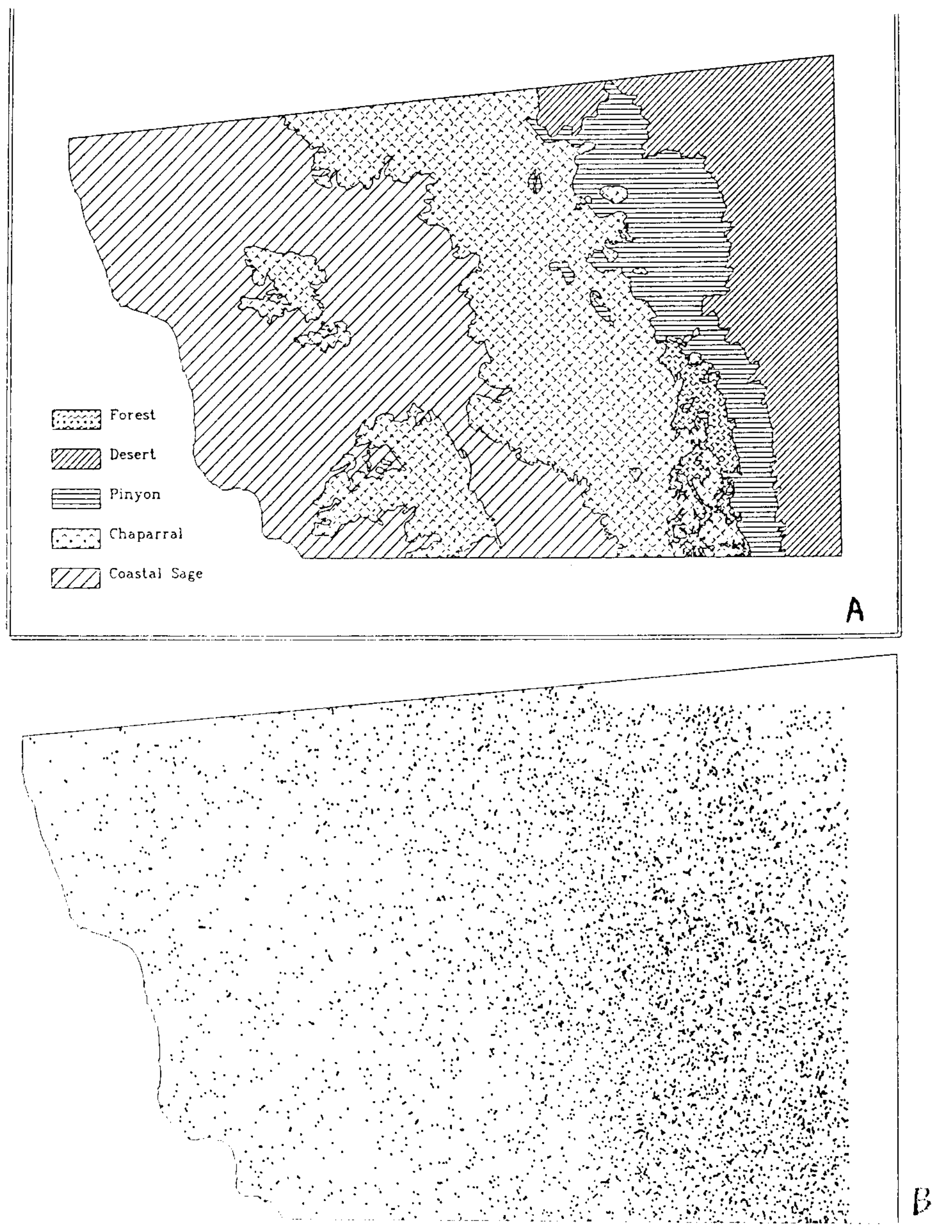


Fig. 4. A) Vegetation of the Sierra Juárez. The crest of the range (alt. 1100–1600 m) follows closely the eastern boundaries of chaparral or conifer forest. The eastern escarpment drops steeply to the Sonoran Dessert. The western slope descends gently toward the Pacific Ocean. B) Lightning detections for the Sierra Juárez region from July to September, 1985-1990.

with prevailing southerly upper winds. To the west of the mountains, precipitation decreases rapidly to <10 mm along the entire length of the coast from San Quintín to the International Border.

Distribution and rates of detection of lightning

Over short time scales, the detection of lightning reflects the paths and magnitudes of individual thunderstorm cells. However, over periods of weeks or months, the distribution of lightning strikes indicates regional circulation, which presents a uniform gradient of lightning strike densities (Figs. 4B, 5B).

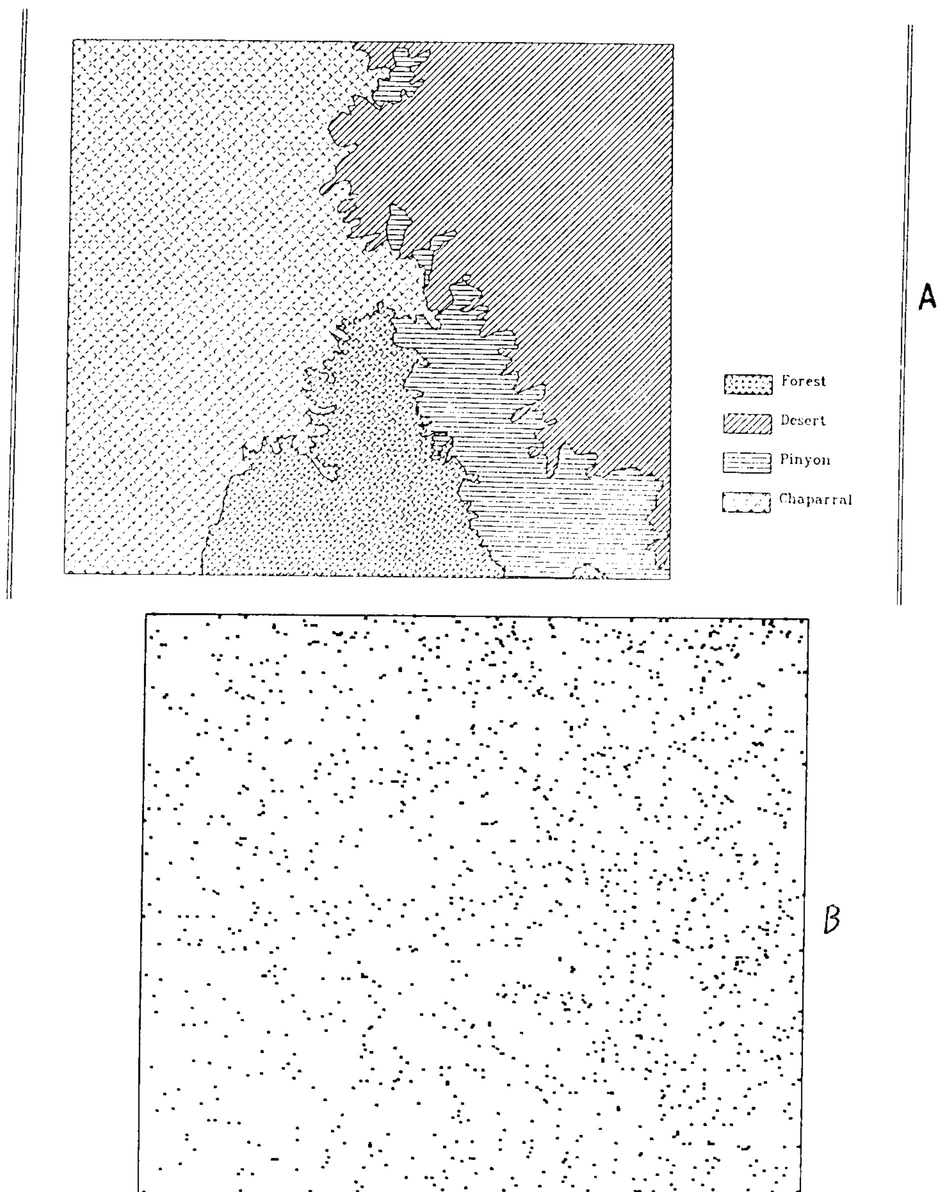


Fig. 5. A) Vegetation of the Sierra San Pedro Mártir. The crest of the range (alt. 1700–3000 m) follows closely the eastern boundaries of chaparral or conifer forest. The eastern escarpment drops steeply to the Sonoran Desert. The western slope descends to ca. 1000 m on the west margin of the inset. B) Lightning detections for the Sierra San Pedro Mártir from July to September, 1985–1990. The eastern terminus of the road track is at the Observatorio Astronómico Nacional.

Sierra Juárez

LD densities are greatest in updraft zones along the eastern escarpment, then decrease gradually to the west as cells dissipate under stabilizing westerly valley–wind systems and sea breezes from the Pacific ocean (Fig. 4; Table 1). The annual frequency of LD's for the entire range averaged 1.0 discharges $(1000\ \mathrm{ha})^{-1}\ \mathrm{year}^{-1}$, and range from 2.0 – 2.3 $(1000\ \mathrm{ha})^{-1}\ \mathrm{yr}^{-1}$ in piñon and conifer forests along the crest of the Sierra Juárez to 1.3 $(1000\ \mathrm{ha})^{-1}$ in chaparral and 0.4 $(1000\ \mathrm{ha})^{-1}\ \mathrm{yr}^{-1}$ in coastal sage scrub along the coast. LD's along the coast probably reflect rare events of unusually unstable air masses. LD rates also decrease slightly along the margin of the Sonoran Desert to the east. The highest LD frequency occurred in the climatically wettest area around Laguna Hanson. There is evidence of a subtle second axis of maximum lightning detections along near–coast ranges southeast of Bahía Todos Santos, especially in 1985, 1987 and 1990.

Table 1. Frequency of lightning detections (LD) and lightning detection density (D) per 1000 ha in the Sierra Juárez and Sierra San Pedro Mártir (July–September)[1].

SIERRA JUAREZ

Vegetation type and area (ha × 1000)	Costal sage 369.9		Chap-arral 311.5		Conifer forest 20.6		Pinyon 103.6		Total 805.6	
Year	LD	D	LD	D	LD	D	LD	D	LD	D
1985	172	0.5	444	1.4	55	2.7	336	3.2	1007	1.3
1986	152	0.5	401	1.3	62	3.0	246	2.4	861	1.1
1987	276	0.7	301	1.0	28	1.4	113	1.1	718	0.9
1988	114	0.3	425	1.4	61	3.0	227	2.2	827	1.0
1989	47	0.1	408	1.3	35	1.7	143	1.4	633	0.8
1990	210	0.6	399	1.3	40	1.9	203	2.0	851	1.1
TOTAL	971		2378		281		1268		4897	
Mean yr^{-1}	161	0.4	396	1.3	47	2.3	211	2.0	816	1.0

SIERRA SAN PEDRO MARTIR

Vegetation type and area ha × 1000)	Chap arral 37.4		Conifer forest 12.2		Pinyon 10.9		Total 60.5	
Year	LD	D	LD	D	LD	D	LD	D
1985	59	1.6	34	2.8	94	8.7	187	3.1
1986	68	1.8	14	1.2	17	1.6	99	1.6
1987	22	0.6	3	0.3	4	0.4	29	0.5
1988	49	1.3	20	1.7	13	1.2	82	1.4
1989	113	3.0	40	3.3	22	2.0	175	2.9
1990	137	3.7	56	4.6	60	5.5	253	4.2
TOTAL	448		167		210		825	
Mean yr^{-1}	74.6	2.0	27.8	2.3	35.0	3.2	137.5	2.3

[1] Source: Bureau of Land Management, Boise Interagency Fire Center, Boise, Idaho. The modal fire size in Baja California chaparral and conifer forests is postulated to be 1000 ha, based on recent history of fire (Minnich, 1989).

San Pedro Mártir

The distribution of LD's in SPM were similar to SJ (Fig. 5; Table 1). Discharge densities are highest on the east escarpment and summit plateau, and decrease slightly to the west along the Pacific slope. Average annual frequencies were 3.2 $(1000\ \text{ha})^{-1}\ \text{yr}^{-1}$ in piñon forest, 2.3 $(1000\ \text{ha})^{-1}\ \text{yr}^{-1}$ in conifer forest, and 2.0 $(1000\ \text{ha})^{1}\ \text{yr}^{-1}$ in chaparral. We have observed that convection occurs mostly along the eastern escarpment, and that a secondary line of thunderstorms forms along the western rim of the Plateau. Cells moving off the plateau to the west and northwest usually dissipate rapidly. LD rates were lower and more randomly distributed in 1986 and 1987 than during the other years.

The pattern of lightning detection in 1990 parallels total precipitation amounts. That summer, LD rates were greatest along the eastern escarpment, remained high across the plateau, and then decreased rapidly along the western escarpment.

Precipitation from July to September (Table 2) ranged from 150–200 mm on the plateau, then decreased westward to 60 mm at 1500 m and 6 mm at Rancho Santa Cruz (lat. 32° 50', long. 115° 38') on the west base of the Sierra (unpublished bulk rain gauge data).

Table 2: Precipitation totals (mm) in the Sierra San pedro Mártir[1].

Station/ALT (M)	S. Cruz 950	West Slope 1500	West Slope 2000	West Plat 2500	Central Plat 2400	East Plat 2700	North[2] Plat 2200	South[2] Plat 2350
Jul 1–Jul 6	0	0	0	0	0	0		
Jul 6–Jul 21	0	6.6	32.5	33.3	21.3	81.5		
Jul 21–Aug 11	0	0.8	30.0	51.4	26.7	35.5		
Aug 12–Aug 29	6.0	8.3	56.1	54.6	15.9	18.0		
Aug 29–Sep 5	0	25.4	69.3	38.1	78.7	50.0		
Sep 5–Sep 13	0	19.7	ND	28.5	26.9	20.0		
Sep 13–Sep 30	0	0.8	0	0	0	0	140.7	109.2
Jun 14–Sep 30	6.0	61.6	187.9+	205.9	169.5	205.0	140.7	109.2

[1] Unpublished data

[2] Remote stations, measurements twice a year in October and May.

(Plat = Plateau)

Interannual variability in lightning detection rates

Interannual LD rates (Table 1) for the entire SJ ranged from 0.8 to 1.3 $(1000\ \text{ha})^{-1}\ \text{yr}^{-1}$. Annual detection rates in SPM varied an order of magnitude, from 0.5 to 4.2 strikes $(1000\ \text{ha})^{-1}$. Since convection is dependent on local mesoscale circulations, the day-to-day areal coverage, location, and magnitude of thunderstorms is often very similar. Thus, the annual variation in LD rates is probably more related to the frequency of days of thunderstorm activity than to fluctuations in air mass stability.

Interannual fluctuations in thunderstorms and Mexican monsoon rainfall correlate with El Niño/Southern Oscillation (EN/SO) events. During El Niño events, abnormally warm ocean waters off Peru and Ecuador displace the ITCZ to the south of its normal summer position, which decreases summer rain in Baja California (Reyes and Rojo, 1985, Reyes *et al.*, 1988). However, some of the wettest summers in the southwestern United Sates correlate with EN/SO

events due to abnormally warm sea-surface temperatures along the California Current. This may encourage abnormal northward penetration of Mexican west-coast tropical storms along the Pacific coast and Gulf of California (Smith, 1986).

Discussion

Lightning detection data clearly demonstrate that cloud-to-ground lightning is common and can be a significant source of wildland fires in chaparral and conifer forest ecosystems in the mountains of northern Baja California. However, the role of lightning in establishing fires is influenced by the temporal characteristics of the vegetation. Fire regimes are inherently cyclical because the combustion reaction removes fuels responsible for this form of disturbance. As a consequence, the interval between fires is partially dependent on a refractory period in the vegetation–the time between a burn and when the vegetation again becomes sufficiently flammable to carry fire under normal weather conditions.

The span of the refractory period, of course, depends on the kind of vegetation. This is illustrated by general ecosystem models for short- and long- refractory period ecosystems (Minnich, 1988). A short refractory period ecosystem, e.g., grasslands that form cured fuels during the dry season, becomes flammable again in a few years, and fire return intervals are determined by ignition frequencies. At the landscape scale, the vegetation is uniformly flammable regardless of previous fire history. A statistically stationary disturbance pattern develops in which all sites have an equal probability of burning: fires spread and overlap one another randomly. The relationship between the number of fires and their size is also random. In long refractory period ecosystems, e.g., chaparral and forests, the vegetation becomes inflammable only after decades of successional regrowth. As a consequence, fire is a dynamic process which is spatially non-stationary. The probability of fire varies nonrandomly because of the previous history of fires and the differential accumulation of fuel in the vegetation mosaic.

From these considerations, it becomes clear that the importance of lightning increases as the refractory period of the vegetation increases. The longer it takes for vegetation to become inflammmable, the lower the lightning rates required to provoke fires.

Long refractory period/nonstationary fire regimes of chaparral and conifer forests

The geographic pattern of fires in chaparral and conifer forests exhibit a long refractory period/nonstationary regime. When chaparral burns, most above-ground biomass is destroyed because of the horizontal and vertical continuity of fuels (Philpot, 1977). In conifer forests, ground fires remove needle litter and shrubs for a few decades. The probability of short-term fire recurrences in both ecosystems is low until fuels redevelop during postfire succession. The twentieth century fire history of BCA, especially when compared to fire history in adjacent SCA where fires have been suppressed since 1900 (Minnich, 1983, 1989)- reveal four evidences of nonstationary fire regimes:

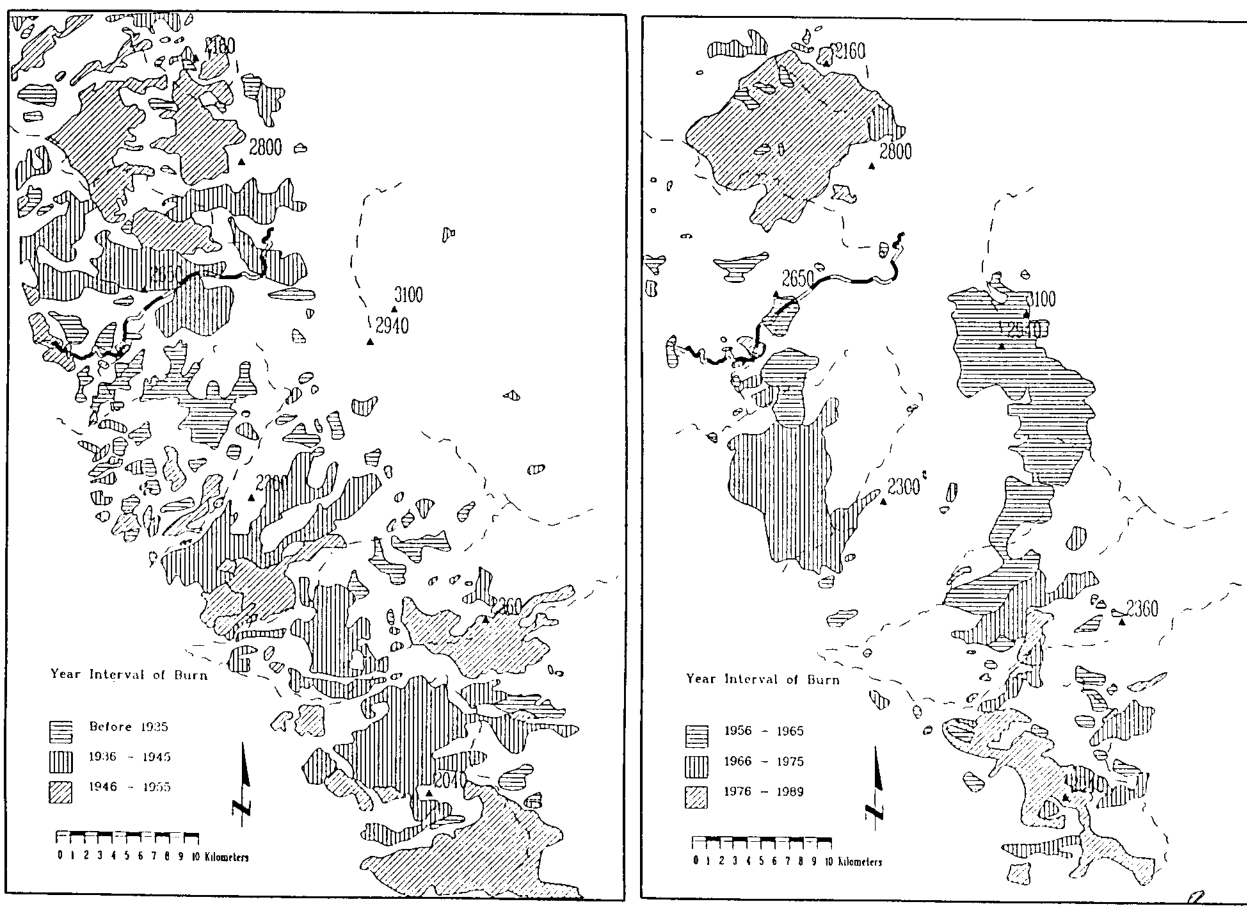
There is a negative relationship between the number of fires and fire size. In NBCA there were numerous fires (2011> 15 ha, Table 3) but mostly small (mean < 1000 ha) in NBCA, few (373) and large (> 10,000 ha) in SCA. In NBCA, burn sequences formed extremely narrow overlap zones in which the progress of fires was prevented by fuel limitations in previously burned areas. Numerous small fire events fragment stands into a fine mixture of age classes, a process that appears to preclude large fires. In SCA, suppression has reduced the number of burns since 1910: this has resulted in a coarsening of the mosaic (Minnich, 1983). Consequently, fires have spread long distances without interruption from previous burns. Fire perimeter maps of SPM

(Fig. 6A, B) show a similar fire regime to SJ. There were 207 burns in the LD database area and 643 for the whole range between 1920 and 1989 (Table 4). Most chaparral and conifer forests have burned at least once since 1920, and several areas have burned twice. Fires ranged to as large as 8000 ha, but most were less than 3000 ha.

Table 3. Number of Burns in the Sierra Juárez, 1920-71.[1]

Period	No. Burns	Burns Yr^{-1}
1920–37	864	48.0
1938–55	739	41.1
1956–71	408	27.2
Total	2011	38.7

[1] From Minnich (1989).



A B

Fig. 6. Fire perimeters deduced from matching aerial photographs over a span of time in the Sierra San Pedro Mártir. A) 1920-1956. B) 1956-1989.

Table 4. Number of burns (> 15 ha) and burn area (ha) in the Sierra San Pedro Mártir, 1920–90.

	North of Lat. 31°[1] (60,500 ha)			Entire Range (174,900 ha)		
Period	No. Burns	Burns Yr^{-1}	Burns[2] Area	No. Burns	Burns Yr^{-1}	Burn[3] Area
1920–42	71	3.5	19,770	200	8.7	53,270
1943–56	69	4.9	16,475	184	13.1	49,075
1956–71	32	2.0	3,295	162	10.1	17,665
1972–89	35	1.9	16,475	97	5.4	37,245
Total	207		56,015	643		157,255
Ave.		3.0			9.2	

[1] Portion of SPM within lightning detection database.

[2] Fire rotation periord $= \frac{\text{vegetation area}}{\text{burn area}} \times 70$ years = 82.4 yr.

[3] Fire rotation period = 77.9 yr.

Short–term fire recurrences are rare. Local recurrence intervals vary considerably due to weather (Minnich and Dezzani, 1991). Thus, it is possible that a stand will burn at a young age in dry windy weather, but not in less extreme conditions. As fuels build up with succession, pyrolysis is possible both during extreme weather and within the normal mode of the weather spectrum. Still, chaparral and conifer forests almost never burn in < 20 yr and only occasionally in < 40 yr.

There is a similarity of average regional fire return intervals in SCA and SJ (ca. 70–80 years) (Minnich, 1989), despite large differences in ignition rates. Fire rotation periods were nearly the same in SPM (Table 4). Comparable burn intervals under different ignition frequencies is evidence that fire regimes are driven more by the fuel dynamics of the ecosystem than by ignition rates.

Average intervals between burns vary with climate, vegetation productivity and fuel accumulation rates. Fire recurrence intervals are shortest (50–70 yr) on the mesic Pacific slopes of the SJ and SPM, and longest in pinyon forests on the arid leeward slopes which burn at intervals of 200–300 years (Minnich, 1989).

The role of lightning in chaparral and conifer forest ecosystems

The importance of lightning in the fire regimes of chaparral and conifer forests was evaluated by comparing the rate of LD with the mean regional vegetation recuperation period (= fire return interval SJ = 70 yr, NSPM = 83 yr) and the modal fire size (ca. 1000 ha). If one assumes that one lightning strike initiates a 1000–ha burn, then LD rates greatly exceed the frequency of burns during the 20th century in SJ and SPM (Table 5). In chaparral, pinyon, and conifer forests of the SJ, the average regional LD rates for 1985–90 would yield over 45,815 strikes during the refractory period of 70 years. Each 1000 ha patch would be struck 105 times, or about 1.5 times annually. There were 16.9 times as many lightning discharges as the projected number of burns (2707) over the refractory period. In the northern SPM, the 1985–90 lightning incidence of 3 discharges per 1000 ha would result in 11,275 strikes, or 187 events per 1000 ha during the 82 yr refractory period. There were 46 times as many discharges as burns. If the northern SPM LD rates are extrapolated to the remainder of the range, this would yield 22,924 lightning strikes over the refractory period. Again, LD rates greatly exceed the frequency of burns.

Table 5. Projected lightning detection (LD) and lightning fire frequencies (L), over fire rotation periods (R) and a modal fire size of 1000 ha in the Sierra Juárez and Sierra San Pedro Mártir.

Vegetation area	Sierra Juárez	Northern Sierra San Pedro Mártir	Sierra San Pedro Mártir[2]
(thousands of ha)	301.5	60.5	174.9
Fire rotation period (YR)	70	82	78
	LD	LD	LD
Mean LD/yr[3]	654.5	137.5	397.5
Projected LD frequency per fire rotation period (LD_R)[4]	45815	11275	22924
Projected LD_R density 1000 ha^{-1}[,5]	105.2	186.7	171.1
Projected LD_R density 1000 $ha^{-1} Yr^{-1}$	1.5	3.1	3.1
Projected burn frequency per fire rotation period (B_R)[6]	2707.1	242.5	781.2
Projected lightning fire frequency per fire rotation period (L_R)[7]	1604.0	394.6	1047.3
$L_R/F_R \times 100$ (%)	59.3	162.7	134.1
LD_R/B_R	16.9	46.5	38.3

[1] Sierra San Pedro Mártir within lightning detection database (> 31°N).

[2] LDs for the entire range, assuming equal lightning detection densities as in the northern San Pedro Mártir.

[3] From Table 1.

[4] Annual LD flux × R

[5] Modal fire size in Baja California chaparral and conifer forests (Minnich, 1989).

[6] $B_R = B_A \times \frac{R}{S}$

where:

B_R = projected frequency of burns per fire rotation period

B_A = actual frequency of burns > 15 ha (from Tables 3 and 4)

(SJ = 1920–71, 51 years)

(SPM = 1920–90, 70 years)

R = rotation period

S = study period

[7] Projected LD_R frequency × 3.5% ignition rate (from Table 6)

Not all discharges, of course, result in the establishment of fires. Lightning often strikes non-flammable rocky sites and peaks and lightning fires are prevented by rainfall or humid weather associated with thunderstorms. However, the thunderstorm season coincides with summer drought; during that time the chaparral and pine forests are dry. Because advection of tropical moisture in unstable air masses tends to be greatest in the mid–troposphere (convective cloud bases range from 3000–4000 m), relative humidity normally remains below 40% except during brief showers (Ryan, 1983; Minnich, 1988). Since fires seldom recur before 20–40 years, and lightning strikes 1000 ha patches 1–3 times per year, the majority of discharges will not establish fires for lack of fuel, especially during early succession. Thereafter, fire establishment may increase either linearly or exponentially. However, the lack of fire history records in Baja California precludes direct analysis of the proportion of lightning discharges that set fires.

Rates of lightning detections versus lightning fires in southern California

U. S. Forest Service records for National Forest in southern California show that lightning fires, most of which consisted of trees on fire or flames on ground fuels, are suppressed at a small size. Lightning fires are most frequent in the inland ranges, with fewer events toward the coast (Komarek, 1968; Keeley, 1982). The low incidence of fire in coastal areas, however, may be related to changes in lightning discharge features due to urbanization. Trees and other vegetation that formerly ignited fires have been replaced by well–grounded powerlines, transformers and buildings (Minnich, 1987 b). Although nearly all lightning fires are suppressed at a small size in SCA, the frequency of lightning fires versus LD's can be used to estimate the potential of lightning for establishing burns. We compared the annual frequency of lightning fires with LD data for the San Bernardino Mountains and San Jacinto Mountains, 100–150 km east of Los Angeles. The resolution of LD triangulation methods is establishing LD locations (5–8 km) did not permit correlation of individual LD's with lightning fires. However, resolution was sufficient to correlate regional LD fluxes with seasonal lightning fire frequencies (Table 6). It was found that the annual percentage of LD's initiating burns varies from 1.2–3%, although ignition efficiencies were 8–11% in both ranges in 1987 (1985–90 mean = 3–4%). Assuming that lightning fire initiation rates are similar in BCFA, and that fire starts enlarge into major burns (e.g., the postulated 1000 ha modal fire size), the frequency of lightning–initiated burns in SJ would be similar to the actual number of burns (Table 6). In SPM, there would be three times as many lightning fires as burns. The efficiency of lightning in initiating fires required to account for recent fire history is only 5 of discharges in SJ and 2% of discharges in SPM. Thus, the SCA lightning fire incidence data demonstrates that lightning could be solely responsible for the high frequency of burns seen presently in SJ and SPM.

The LD rates for 1985–90 may not be representative of the long–term average because of natural climatic variability. Large interannual variability in LD rates can be expected due to rare, but great thunderstorm outbreaks in which LD rates during a few days may exceed annual rates. The Stanislaus National Forest of California, for example, sustained thousands of lightning fires over a few days during September, 1987. An outbreak of thunderstorms in the San Gabriel Mountains, north of Los Angeles, resulted in numerous lightning fires and 40,000 ha burned on July 19–20, 1960. Outbreaks of this magnitude did not occur during the 1985–90 LD database period. The annual rate of suppressed fires in the San Bernardino National Forest for the 6 yr LD period was 38.7 or 72% of the 1950–1990 annual mean (53.6, file data of the San Bernardino National Forest). Thus, the average long–term lightning–discharge rates in BCFA may be greater than the 1985–90 rates reported here.

Table 6. Frequency of lightning detections (LD)[1] and suppressed lightning fires[2] in the San Bernardino and San Jacinto Mountains, southern California (July–September).

	Sierra San Bernardino				Sierra San Jacinto			
Year	Lightning detections	Freq/ 1000 ha	Linghtning fires	% IGN[3]	Lightning detections	Freq/ 1000 ha	lightning fires	% IGN[3]
1985	562	0.84	17	3.0	300	0.89	8	2.7
1986	431	0.64	16	3.7	358	1.07	6	1.7
1987	281	0.42	23	8.2	170	0.51	20	11.7
1988	1140	1.70	32	2.8	638	1.89	12	1.9
1989	253	0.38	3	1.2	204	0.61	6	2.9
1990	347	0.52	23	6.6	300	0.89	9	3.0
Total	3014	4.50	114		1970	5.86	61	
means	502	0.75	19.7	3.8	328	0.97	10.2	3.1

[1]Source: Bureau of Land Management, Boise Interagency Fire Center, Boise, Idaho.

[2]Source: San Bernardino National Forest. Area boundaries, San Bernardino Mountains: north border, 34° 20'; east border, 116° 35'; south border, 34° 00'; west border, 117° 30'. San Jacinto Mountains: north border, 33° 55'; east border, 116° 20'; south border, 33° 30'; west border, 116° 55'.

[3]Lightning fires – lightning detection × 100, IGN = ignitions.

Conclusion

The observation by foresters and ecologists that lightning fires are reponsible for little of the total area burned in the United States (< 5%) has been cited as evidence for long fire intervals and large fires in prehominoid times (Dodge, 1975; Keeley and Zedler, 1978; Keeley, 1982; Stewart, 1956; Lewis, 1973; Vankat and Major, 1978; Timbrook *et al.*, 1982). Consequently it is deduced that the majority of fires that occur in Baja California are produced by man. We believe the potential of lightning fires in SCFA may not be fully realized due to fire control management. The kind of weather associated with large uncontrollable fires in SCFA is significantly different from the weather occurring when fires are suppressed at a small size; this includes most lightning fires (Minnich and Dezzani, 1991).

Although thunderstorms are most frequent during the summer when the vegetation is desiccated, lightning ignitions seldom establish themselves immediately into burns because of high humidity normally responsible for the associated convection. Hence, they are easily extinguished. Indeed, all lightning fires in the San Bernardino and San Jacinto Mountains during 1985–1990 were extinguished at < 15 ha. Anthropogenic ignitions can occur under the most hazardous weather conditions and then are much more likely to escape initial suppression efforts.

In an unmanaged fire regime such as in BCA, smoulders can persist over time spans that capture most of the climatic variability. Previous studies of fire behavior in chaparral and conifer forests of southern California before fire control (Minnich, 1987 b, 1988) have shown that lightning fires could store for weeks in large fuels (logs, standing trees) and expand with the arrival of dry weather. In BCA fires have also persisted for weeks to months, alternatively spreading and smouldering through the chaparral and forests. For example in SPM, a 1956 burn in Picacho del Diablo spread for five weeks (Werner, 1957). In 1989, a fire spread through

the north end of SPM from June to August. In prehistoric times smouldering behavior was probably characteristic because summer rains capable of extinguishing fires are rare, and weather is sufficiently dry to sustain burning and smouldering through the entire dry season.

A long duration fire propagates slowly along narrow interconnected bands which leave numerous "islands" of unburned vegetation. One lightning strike may produce many burns. In this manner, the resulting mosaic may come about from a relatively small number of ignitions (Minnich and Dezzani, 1991). Thus, in evaluating relationships between ignition rates and the size and frequency characteristics of a burn mosaic, the frequency of lightning should not be treated as equivalent to that of burns.

Lightning detection data, burn history, and fire behavior indicate that lightning from summer thunderstorms are a ubiquitous source of ignition for the combustion of chaparral and conifer forests of northern Baja California. The ratio of lightning detections to lightning fires reveals that a very low proportion of lightning ignitions leading to fires (2–3%) is sufficient to establish the complex fire regime now seen in the chaparral and conifer forests of Baja California. The low percentage of lightning strikes that initiate fires should not be interpreted as evidence for the ineffectiveness of natural discharges. Rather, it is evidence that the landscape is supersaturated by lightning, such that few discharges strike vegetation capable of supporting fire due to the long refractory period of the vegetation. Higher lightning densities should not increase fire activity. As a corollary, anthropogenic burning is unlikely to have significant impact in forest and chaparral ecosystems in Baja California.

Implications for management in Baja California

In Baja California, both federal and state agencies responsible for forest management have implemented fire suppression with the objective of protecting the forests. Since it is considered that man is one of the most important factors in initiating fires, there has been increasing pressure put on cattlemen to refrain from setting fires.

In mediterranean regions, burning has long been used by cattlemen as a management tool (Godron *et al.*, 1981; Le Houerou 1981; Trabaud 1981, 1983); it is also a common practice in Baja California. The aim of burning is to open vegetation in advanced successional stages, give access to cattle, and permit growth of herbaceous vegetation and resprouting of shrubs. This increases the availability of browse and permits easier and better management of cattle. Following a policy of total fire suppression will be counterproductive if the objective is conservation of forests. Fire can be suppressed only in the short term, since in the long term the accumulated fuel will eventually burn, provoking larger, more intense and devastating fires (Minnich 1983; Trabaud, 1983). If landholders are punished because fires occur in their land, false accusations will become inevitable because lightning is a more important source of fire than has been realized. Given that the cattlemen's need to open the chaparral coincides with the presence of a mature vegetation, the practice of controlled burning may be a good option for management in a region where natural fire has shaped landscapes.

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